

# **AUV Self Noise Control and Acoustic Signature Experimental Analysis**

J. M. Cuschieri, D. Vendittis  
S. Frandsen  
Department of Ocean Engineering  
Florida Atlantic University  
Boca Raton, FL 33431

Phone: (561) 297-3438 fax: (561) 297-2659 email: [joe@jmc.oe.fau.edu](mailto:joe@jmc.oe.fau.edu)  
Phone: (954) 924-7275 fax: (954) 924-7233 email: [venditti@seatech.fau.edu](mailto:venditti@seatech.fau.edu)

Award Number: N000140010274  
<http://www.oe.fau.edu>

## **LONG-TERM GOALS**

The long-term goals of this work are to develop a modeling tool that can be used in the design of an AUV to estimate the noise signature given a set of operating conditions. The same tool can be used to include noise mitigation procedures in the design, if the estimated signature does not satisfy some predefined set conditions. It is the intention of this work that the modeling tool developed would be directly integrated into engineering design tools. This will minimize the need of input from the engineering designer of the AUV.

## **OBJECTIVES**

Self-noise of an AUV has important implications for operational requirements and for on-board acoustic and other sensors. Little consideration has been given to the issue of self-noise in the design of AUV's. Typically, the design and material of the hull, the configuration of attachment points and the selection of propulsor and control surface servomotors are primarily being driven by functional and mechanical operational requirements. Only an ad hoc approach has been used in the past to select noise signature mitigation procedures.

The objectives of the work are therefore:

- (a) To continue developing a numerical model to estimate the acoustic radiation from an OEX AUV at low to medium frequencies. This would specifically address the tonal characteristics.
- (b) To explore the use of high frequency modeling techniques (such as Statistical Energy Analysis - SEA) to extend the prediction of the self-noise to high frequencies where tonal characteristics are non-existent.
- (c) To perform measurements on an AUV OEX model using the FAU reverberant test tank to verify the low, medium and high frequency estimates of the acoustic signature from the numerical model.
- (d) To explore the influence of coatings to reduce to acoustic signature.
- (e) To explore the use of active control for the suppression of the low frequency tonal noise.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2001</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2001 to 00-00-2001</b>	
4. TITLE AND SUBTITLE <b>AUV Self Noise Control and Acoustic Signature Experimental Analysis</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Department of Ocean Engineering,,Florida Atlantic University,,Boca Raton,,FL, 33431</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT <b>The long-term goals of this work are to develop a modeling tool that can be used in the design of an AUV to estimate the noise signature given a set of operating conditions. The same tool can be used to include noise mitigation procedures in the design, if the estimated signature does not satisfy some predefined set conditions. It is the intention of this work that the modeling tool developed would be directly integrated into engineering design tools. This will minimize the need of input from the engineering designer of the AUV.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT  <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES  <b>9</b>	19a. NAME OF RESPONSIBLE PERSON
a REPORT <b>unclassified</b>	b ABSTRACT <b>unclassified</b>	c THIS PAGE <b>unclassified</b>			

## **APPROACH**

The work in the last year mainly focused on an experimental analysis of the acoustic signature of an Ocean Explorer class AUV. The experimental analysis performed consists of three parts. The first part reports the measurements performed in an open water environment at NSWC in Lake Pend O'reille, Idaho. The second part reports on measurements performed at the FAU test tank on a mock model of the AUV and the third part reports the measurements also in the FAU test tank of the AUV under typical operating conditions. The model measurement results were also used to verify the prediction capabilities of a numerical FE model of the AUV using the reciprocity method. The measurements in the FAU tank considered different operating conditions and different mounting of the podule inside the AUV. The podule contains the main mechanical components of the AUV, which are the propulsion motor and the control surface motors. Also considered in these measurements are the influence of the propeller and the influence of covering the aft section of the AUV with a compliant layer. The results of this analysis show that the type of mounting of the podule is not very significant and that significant energy is transferred through the water trapped in between the podule and the AUV hull. Furthermore, the propeller has a significant influence on the acoustic signature since it generates distinct tones. These tones were also observed in the results of the open water measurements.

## **WORK COMPLETED**

Evaluation of the Lake Pend O'reille data was the starting point in this year's work. Coinciding with the radiated noise measurements, a numerical model of the aft section of the AUV consisting of finite element (FE) components and boundary element (BE) components that included the surrounding acoustic medium was developed by DeBiesme [1]. This FE and BE numerical model was reported in the last annual report, and was also used this year, together with experimental data on a physical model to verify the results. A technique called mechano-acoustic reciprocity is used to compare the ratio of radiated pressure due to a point force predicted from the numerical FE model to an equivalent ratio, measured experimentally. In the experiment, the acceleration induced on the physical model due to a sound source is measured.

The current AUV vibration isolation system has been evaluated using different isolation mounts. Extensive vibration and acoustic measurements for the AUV in different running configurations have been conducted in an effort to better understand the AUV signature measured at lake Pend O'reille. The AUV design is unique compared to other small submersibles or submarines because the machinery noise is surrounded by water inside the vehicle. This complicates the analysis of radiated noise transmission because it is a combination of noise transmitted through the isolation mounts, as well as through the water.

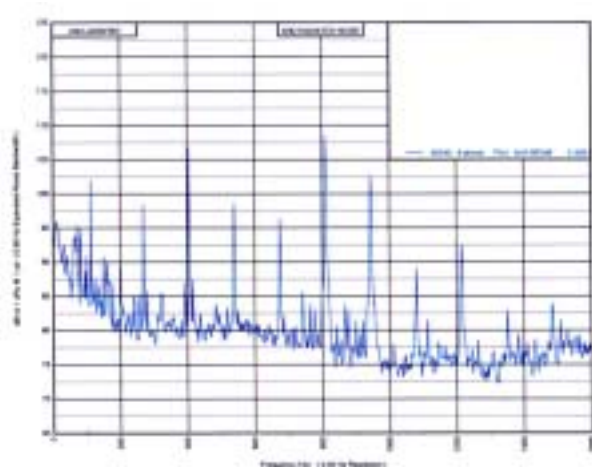
## **RADIATED NOISE MEASUREMENTS**

In May 1999, radiated noise measurements of an OEX Class 2 AUV were conducted at the Naval Surface Weapons Center (NSWC) facility located at Lake Pend O'reille in Bayview, Idaho. The radiated signature of the OEX II in full running configuration was measured in a quiet, deep, open water environment. The AUV OEX II Drake was run at speeds of 3 and 5 knots, respectively, past a line of hydrophones (4 phones were used) at depth of 400 feet. Measurements were taken of the background noise before each run. During the run of the AUV, the vehicle noise was measured. Three runs were considered successful, one at three knots and two at five knots. Narrowband data,

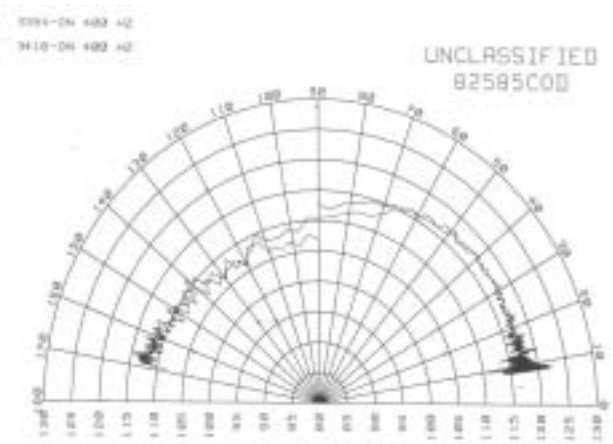
1/3-octave data, and directivity data were generated from these three runs. There were also LOFAR displays and Sanborn chart recordings.

### Data Observations

The Narrowband data showed a number of tonals from low frequencies up to 6000 Hz for the 5-knot runs (Figure 1). These start at low frequencies up to 4000 Hz. The tonals are spaced evenly at about 130 Hz. Initially, these tonals were considered to be possible multiples of shaft rate. The motor in the AUV was new with higher horsepower than previous AUVs tested. Another possibility is excitation of shell modes due to the vibration of the vehicle in running configuration.



**Figure 1: Narrow band data for 5 knot run showing numerous tonal components**

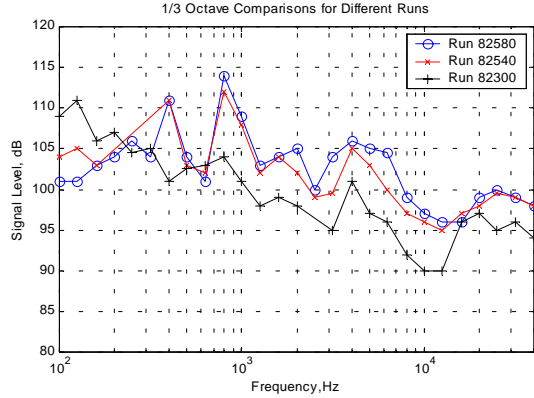


**Figure 2: Directivity plot showing source of noise is higher in the stern direction**

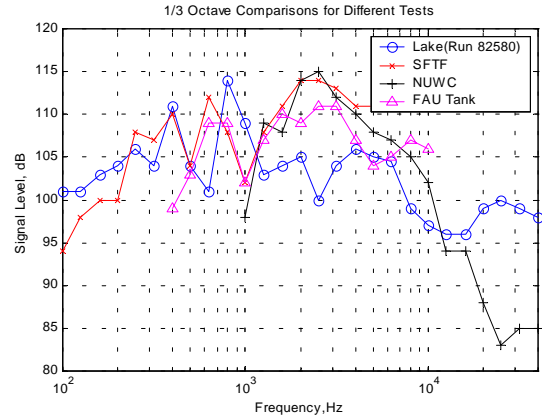
There are two large peaks (107-108 dB) in the narrow band data at 410 and 820 Hz, respectively and these could possibly be caused by resonance of the structure at 5 knots. In Figure 2, the 400 Hz directivity plot shows a level of 120dB at the stern of the vehicle, as compared to 107 dB at the bow. This suggests that the source of noise is primarily from the rear of the vehicle. The highest radiated energy is below 1000 Hz. In general, the AUV puts out a 100 to 110 dB signal level over the 100 to 10,000 Hz frequency range.

### Data Comparisons

The 1/3-octave data for the three runs are shown below in Figure 3. The red and blue plots are the runs at five knots (675 RPM), while the black plot is the run at three knots (500 RPM). The shape is the same, but the higher horsepower speed results in a higher radiated noise signature. The highest levels are in the low frequency range below 1000 Hz due to the numerous narrow band tonals.



**Figure 3: Comparison of OEX II 1/3 octave signal levels for different runs at lake Pend O'reille**



**Figure 4: Comparison of AUV 1/3 octave signal levels for different radiated noise tests**

The 1/3-octave data from Lake Pend O'reille were also compared to previous 1/3-octave measurements on AUVs at SFTF, NUWC, and FAU. The AUV used for each test was not the same. The comparison plot is shown in Figure 4. The radiated noise measurements from the lake are consistent with other measurements. A noticeable difference in the 1/3-octave comparisons is that at 1000 Hz and above, the AUV tested in the lake is quieter than all other systems. This OEX II AUV had the gearbox removed and the podule was soft mounted, which may have attributed to the reduction in the noise at high frequencies. Another noticeable difference in the data comparisons is that at the mid frequency range, the lake data is higher in the 630 and 1000 Hz 1/3-octave bands. This could be due to the narrow band frequency peaks at 410 and 820 Hz, respectively. If the cause of these narrow band tonals could be determined and possibly eliminated, the 1/3-octave levels could go down as much as 10dB based on rough estimates of eliminating the tonals and leaving only broadband noise.

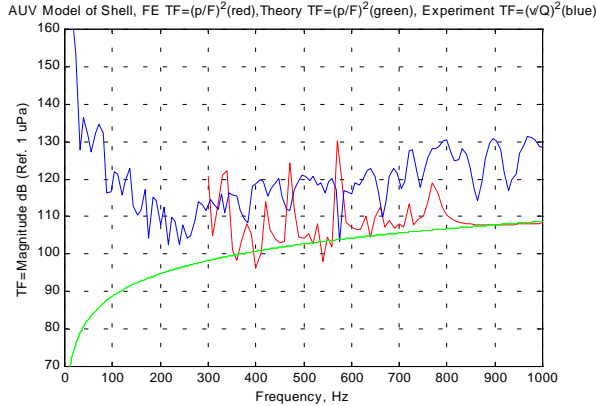
## EXPERIMENTAL ANALYSIS

The primary focus of this investigation is to compare the frequency response function of the radiated pressure predicted by the FE and BE model due to a point force to the frequency response of the measured acceleration on the experimental model due to the pressure from a sound source. The method used for comparison is called mechano-acoustic reciprocity. In addition, the FEA showing the shell natural frequencies (modal analysis) of the AUV model and the effect of air versus water damping of the shell modes (frequency shifts) determined by DeBiesme is compared to the experimental model vibration results in air and water.

Reciprocal measurements in linear, mechano-acoustical systems indicate that the pressure induced in a fluid excited by a force applied to a structure is equivalent to a velocity induced on a structure due to an acoustic volume velocity source [2]. Based on the experiments described in [3, 4, 5], reciprocity is a valid experimental method to verify the direct transfer function predicted by DeBiesme's FE and BE model of the FAU AUV.

## RESULTS

Figure 5 shows the experimentally measured indirect transfer function plotted with the numerical direct transfer function calculated in the FE program. The equipment sensitivities and gain factors for the accelerometer and for the hydrophone respectively were taken into account, and the constant was added to determine the reciprocal transfer function shown.



**Figure 5: Comparison of three transfer functions: numerical FE, experimental, and theoretical**

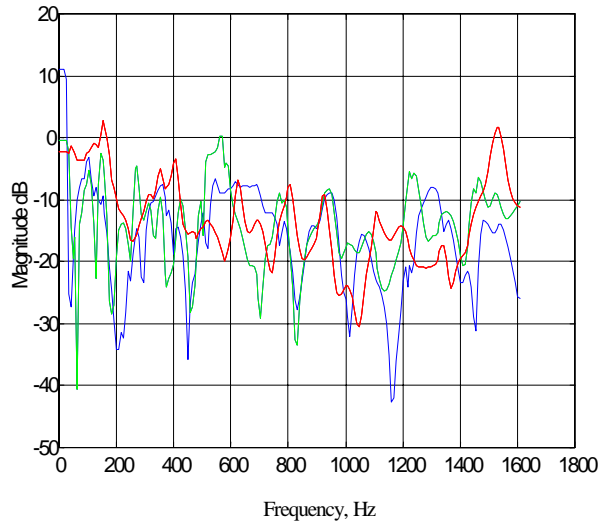


**Figure 6: Different isolation mounts used in model and AUV tests: from left to right: regular isolator, softer isolator, aluminum stud**

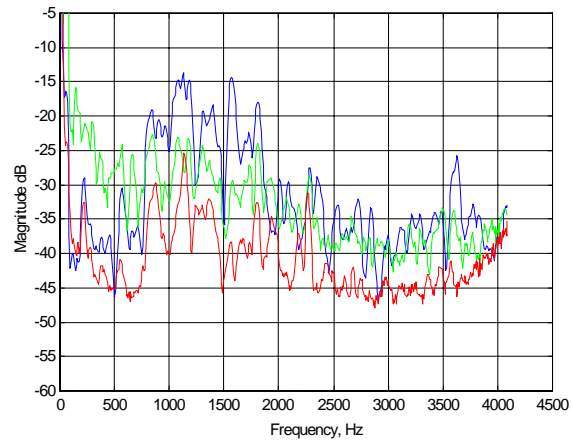
In summary, the reciprocity transfer function and the transfer function predicted by the FE program are not as close as expected. Previous mechano-acoustic reciprocal experiments discussed in the literature [5, 6, 7, 8] indicated that the direct and indirect transfer functions were within 5 dB. In our experiment, the difference was as high as 12 to 15 dB. The main reason attributed to the difference in the measurements is the fact that the models were not exactly comparable. The FE model is closed as compared to the open-ended model used in the experiment. The radiated pressure determined in the BE program is calculated based on the normal nodal displacement of the structure's surface due to a point force. An open ended model would result in free edges that are analytically too difficult for the BE model to handle. Other physical differences are that the plastic deck in the FE model was removed for this analysis; in the experimental model this was not possible since the deck was needed to hold the top and bottom shell together. In addition, the nose cone was designed as a cylinder in the FE model, as compared to the experimental model that was shaped differently.

### Vibration And Acoustic Tests

Three different isolation mounts (figure 6) were used to support the podule in order to determine their effectiveness in reducing the vibrations transmitted to the hull and subsequently reducing the radiated noise.



**Figure 7: Comparison of transfer functions between acceleration measurements made on the podule and on the hull ( $TF=acc2/acc1$ ) for regular isolators, soft isolators and aluminum studs. —: regular isolators, —: soft isolators, —: aluminum studs**



**Figure 8: Acoustic radiation measurements of model using different isolators. —: regular isolators, —: soft isolators, —: aluminum studs**

Figure 7 shows a comparison of the transfer function between an accelerometer on the podule and one on the AUV hull. It shows that the vibration energy transmitted is the same whether the podule is supported on the rubber isolators, or hard mounted. The vibrations transmitted from above the mounts ( $acc1$ ) to the hull ( $acc3$  is approximately 50 cm from  $acc1$ ) are the same with the rubber mounts supporting the podule or hard mounting the podule.

A comparison of the three isolators and their effect on the acoustic radiation measured is shown in Figure 8. The podule hard mounted with the aluminum studs has the lowest acoustic radiation. This is attributed to the fact that the aluminum studs strongly couple the podule to the hull water loading, which reduces the radiation. This also shows that the water path is the dominant path of transmission.

## CONCLUSIONS

Reciprocity was used to evaluate the radiated noise prediction capabilities of the FE and BE numerical model. The experimental and numerical results were fairly reasonable, verifying the use of reciprocity as a reliable experimental method. In addition, the numerical results were compared to analytical results (within 5 dB). Both the experimental and analytical results indicate that the FE and BE numerical model of the AUV is a reliable tool to evaluate the acoustic effects of future AUV modifications.

### **The results of the AUV vibration and acoustic tests:**

- (a) Comparing the vibration transfer functions of in water for all three isolator mounts and for the same excitation with the propeller on and off, one can observe that there is little difference between the three transfer functions. This implies that in water, the stiffness of the isolator does not play a significant role, unlike the results in air. The transmitted energy was the same. This agrees with the model results.
- (b) With the propeller attached, there is a direct vibration interaction between the propeller and the hull that occur at a harmonic of the blade passing frequency.
- (c) Comparing the measured AUV source levels for the regular rubber mounts, soft isolators and the aluminum stud mounts with and without the propeller attached, it appears that the source level is not significantly influenced by the mounts whether with or without the propeller.
- (d) With the propeller attached, the source level is dominated by the motor and the propeller. The contribution from the fin motors is insignificant.
- (e) In the open water and pool tests, it was determined that the source level of the AUV is dominated by propeller harmonics. There are distinct series of equally spaced peaks, the frequency of which can be attributed to a multiple of the blade passing frequency. The separation of the peaks in both signature plots mark the blade passing frequency multiplied by the number of free control surfaces. The fact that the lake data levels and the AUV test tank levels were comparable indicates that the pool measurement set up with the hydrophone approximately one meter away is a fairly accurate method to measure the signal levels of the AUV.
- (f) Using bubble wrap over the podule section of the AUV reduced the signal levels by as much as 15 dB. This test indicated that the AUV is directive and radiating primarily from the podule area containing the main propulsion motor and fin motors. This is important because if a coating were used, only this area would need to be covered. Also, the bubble wrap test indicates that at the low frequencies, propeller noise dominates the signature, but at the higher frequencies, the machinery noise is the significant noise component. This can be investigated further with different coatings used on the model podule and hull. An impedance mismatch can also be created numerically in the FE model and results could be compared. Further tests to evaluate the propeller, since it dominated the acoustic signature are recommended.

### **IMPACT/APPLICATIONS**

This project has a high potential future impact on AUV technology. Successfully completing an approach that can model the acoustic signature of an AUV and which can be directly included in the design of an AUV, would be very important in expanding the types of missions for which an AUV can be employed.

### **TRANSITIONS**

This project is still in its rather early stages and has not yet been transitioned into other areas. However, participation in design meeting with the AUV design team has resulted in verbal input and changes made to the design based on this input.



## RELATED PROJECTS

Related projects to this are the AUV projects at FAU and at other institutions. Interaction with the FAU AUV project occurs on a frequent basis.

## REFERENCES

- [1].Francois-Xavier DeBiesme, “Modeling the Acoustic Signature of an Ocean Explorer Class Autonomous Underwater Vehicle”, MS thesis, Florida Atlantic University, 2000.
- [2].Frank Fahy, Sound Vibration and Structural Radiation, Transmission and Response, Academic Press, 1985.
- [3].T. ten Wolde, “Reciprocity experiments on the transmission of sound in ships”, Ph.D. Thesis, Tech. Univ, Delft Publications, Huogland and Waltman, Delft 1973.
- [4].T. ten Wolde, “On the validity and application of reciprocity in acoustical, mechano-acoustical and other dynamical systems”, Acoustica, 1973, Vol. 28, p23-32.
- [5].H. F. Steenhoeck and T. ten Wolde, “The reciprocal measurement of mechanical-acoustical functions”, Acustica, 1970, Vol. 23, p 301-305.
- [6].T. ten Wolde, “Reciprocity measurement of acoustical source strength in an arbitrary surrounding”, Noise Control Engineering, 1976, Vol 7, p16-23.
- [7].Takaaki Musha, Akira Shinohara, Isao Abe, and Mutsuo Takashima, “Evaluation of acoustic radiation efficiency for hull plate using the reciprocity method”, JSME International Journal, 1994, Series C, Vol. 27, No. 3, p612-615.
- [8].Takaaki Musha and Tatsuo Kikuchi, “Validity of the vibro-acoustic reciprocity method for the measurement of the mechano-acoustical transfer function”, Journal of Acoustical Society, 1998, Series E, Vol. 19, No. 2, p151-153.